ABOUT THE Fe XIV 530.3 nm LINE EMISSIONS OF THE MIDDLE CORona

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ABSTRACT/RESUME

To study the behaviour of non-thermal velocities in the solar corona as a function of radial distances, we first describe new ground-based spectroscopic observations made using a 40 cm aperture coronagraph over a whole range of radial distances (up to heights of 12’ above the limb) and along four different heliocentric directions N, E, S and W. The analysis is limited to the study of the brightest forbidden emission line of Fe XIV at 530.3 nm in order to reach the best possible signal/noise ratio. To make the results statistically more significant, the extracted parameters are averaged over the whole length of the slit, and measurements are repeated five times at each position; the corresponding dispersions in the results obtained along the slit are given. Central line profile intensities and full line widths (FWHM) are plotted and compared to measurements published by other authors but closer to the limb. We found widths and turbulent (non-thermal) velocities of significantly higher values above the Polar Regions, especially when a coronal hole is present along the line of sight. We do not see a definitely decreasing behaviour of widths and turbulent velocities in equatorial directions for radial distances under 0.5 solar radius from the limb. The variation in the high corona is rather flat under 0.5 R\(_{\odot}\) and a correlation diagram indicates that it is different for different regions and different radial distances.

To look above 0.5 R\(_{\odot}\), we shortly describe observations using a specially designed eclipse “long-slit” spectrograph which brought several sets of results in 1994, 1999 and 2001. Eclipse results are in agreement with coronographic measurements but at higher heights they show a significant decrease of FWHM.

We also consider Doppler shifts to look at flows and at oscillations and waves as seen on longitudinal components of velocities. A typical power spectrum deduced from a time series, with a 9 s cadence, is showed to illustrate the existence of short period oscillations. Accordingly, we show that the macro-turbulence is partly resolved everywhere thanks to the analysis of the line profile of this Fe XIV line and that the methods illustrated by these results represent a great potential for future space-born artificial eclipse experiments.

1. INTRODUCTION

Any measurement of non-thermal velocities distributed inside the coronal plasma is a good diagnostic for studying both the origin of the coronal heating and the sources of the solar wind (see e.g. Doschek et al. 2001). Two mechanisms are today widely discussed to explain the high temperature of the corona (see e.g. Phillips, 1995) and how it is maintained:

![Figure 1](image1.png)

Figure 1 – The green-line overexposed image of the eclipse corona of 2001. Ghost images in 2 directions are produced by the narrow pass band filter at the 1% level. The radial gradient of intensities is removed to better show the structure but note that the line emission was recorded up to 3 solar radii from the limb.

a- The dissipation of small-scale electric currents associated to a changing small-scale magnetic field, currently described by the concept of reconnection of magnetic field lines (see Priest and Forbes, 1999). Impulsive heating and sudden local release of energy leading to high temperature effects and transient brightenings are possibly the signature of this mechanism, (see e.g. Smartt, Zhang and Smutko, 1993; Wood et al. 1998). We will not consider this process in this paper, just because it presumably requires good spatial resolution.
observations which are difficult to obtain simultaneously with precise spectroscopic data, especially from the ground. Another reason is that this mechanism certainly operates close to the surface and our coronagraphic and eclipse observations are done well above the surface.

b- Non-linear effects occurring during the propagation of waves inside a magnetically dominated atmosphere and further, in the outermost atmosphere where waves are guided. Waves obviously produce displacements, including unresolved proper motions which can better be studied by measuring Doppler effects seen in the broadened profiles of coronal emission lines. Because of the high level of structuring in the corona as shown on high resolution coronal images, the observed broadening shows the integration effects along the line of sight. However, depending on the importance of waves, a signature at different heights, keeping in mind that the hydrostatic pressure scale, see November and Koutchmy, 1996, is of order of 100 Mm in a $2 \times 10^6$ K corona (or two times less, in a presumably more inner $1 \times 10^6$ K corona), can be searched for. Observations usually have a spatial resolution significantly better than this scale, and their resolution is often comparable or similar to the typical scale of variations of the coronal magnetic field. Accordingly, we can expect some dispersion occurring in the real data when looking at an “instantaneous” line profile, even after integration along the line of sight, due to the finite number of summed contributions along the line of sight at a given moment of observation.

Another important aspect of the coronal dynamics is the outward acceleration of the “bulk” (magnetic) coronal plasma leading to the solar wind. Recent movies made using the beautiful LASCO observations from SoHO, amply demonstrated that a permanent flow with different scales, including the smallest one which is evidently not fully resolved, exists along streamers (movies are available on CDs by ESA and by NASA or using the Web sites of SoHO in USA or Europe). At larger scales, coronal mass ejections (CMEs) are episodically observed, but their study requires more global diagnostics. Here we will not discuss these phenomena any further.

We know for a long time that a solar wind of significantly larger speed originates from coronal holes than from other regions of the Sun (the so-called fast wind is typically a factor of two faster than the slow wind). The mechanism(s) of acceleration operating at some unknown distance from the Sun, here again, is not clear. It has been suggested by several authors that waves outwardly propagating along an approximately radial magnetic field (presumably “open”) could explain the strong wind coming from a large part of the corona (see, e.g. Wilhelm et al. 1998; Tziotziou et al. 1998; see also the recent review by Woo and Habbal, 2002 for an alternative topological configuration). The propagating waves in the corona are believed to have short periods and small amplitudes, just because, low in the corona, magnetic forces dominate pressure gradients of the high temperature (at least $10^6$ K) plasma. Often Alfvén waves coupled with the plasma are suggested (see, e.g. Axford and McKenzie, 1992). They are difficult to resolve but their signature on the line profiles of strong emission lines should be imprinted; associated velocities are usually called non-thermal (or turbulent) velocities and they have been discussed for a long time since all coronal lines are indeed affected.

2. SELECTING THE 530.3 LINE OF Fe XIV

To perform a precise line profile analysis far enough out in the corona, the strongest emission line available, when using a Lyot ground-based coronograph, the forbidden line of FeXIV at 530.285 nm, is the best choice. Note that this really easy to observe line produces a photon flux per resolution element rather comparable to the strongest EUV lines, such as the Fe IX and XI lines at 17.1 nm used currently for coronal imaging from space but with much lower efficiency. This truly coronal emission line is not sensitive to the so-called Doppler dimming effect (see, e.g. Kohl and Withbroe, 1982), such that its profile is directly reflecting line-of-sight velocities inside the corona. In addition, it has been established a long time ago (see Allen, 1946) that the line is measurable in the corona all along large radial distances, a measurement that we fully confirmed using a first CCD eclipse experiment that we performed in 2001. Photometric quality (14 bits) images were taken on line and off line (K+F corona alone) with an interference filter of 0.45 nm FWHM see Fig. 1. The radial behaviour of the 530.3 nm line emissions of Fe XIV, after removing the K+F background, was deduced taking into account all identified instrumental effects. Fig. 2 shows for the 1° time the ratio I(530.3 nm)/K as a function of radial
distances $R_e$ at least up to 4 solar radii from the solar centre. Accordingly, a detailed quantitative analysis of the line profiles can be made up to large radial distances and in the brighter inner corona, a temporal resolution of the order of 0.1 min (with the possibility to search for oscillations) is easy to reach. As a rule, the signal/noise ratio is usually high enough to measure easily any departures from a Gaussian profile and, also, to deduce some effective Doppler shifts from an average profile (see e.g. Tsubaki, 1975 and Koutchmy et al., 1983) with a precision better than 1 km/s. Another advantage of this nearly 2x10^3 K line is that it is produced almost everywhere inside the corona and up to great heights (see Arnaud, 1982 for coronagraphic observations; Kim, 2000; Bocchiàlami and Koutchmy, 2001 for eclipse observations). Many observations were collected with coronographs, both photographically and photoelectrically. Well above the limb, especially in polar regions, the coronal signal obtained with a ground-based coronagraph becomes weak above the so-called aureola background parasitic light level. The use of a very sensitive and linear charge-coupled device (CCD) camera extended in dynamical range makes possible a new way to analyse the line by subtracting the background. Note that the limitation occurring in space due to the limited telemeter rate does not exist at ground-based sites.

Recently, Singh et al. (1999, 2002, 2003) published a series of papers devoted to the analysis of the main coronal lines observed using the Norikura Observatory Lyot coronagraph of 25 cm aperture. CCD spectra were obtained with high signal/noise ratio and the behaviour of the line broadening as a function of height was studied in particular. Impressive results were obtained, very similarly to the earlier classical study of Tsubaki (1975) made with the larger 40 cm aperture coronagraph at Sacramento Peak Observatory, but using photographic film of lower sensitivity. Surprisingly, Singh et al. did not find evidence for increasing amplitudes of non-thermal velocities in the Fe XIV line with height. Instead, they describe some decrease of non-thermal velocities measured from their line profile analysis, for heights up to 140" above the limb. Note that this is still a rather limited range not surpassing two hydrostatic scale heights and that SUMER (SoHO) results reported by Doyle et al. 1999 did show an opposite effect above a polar region. In addition, the study of Singh et al. was limited to bright regions of the corona related to limb coronal enhancement probably overlying sunspots and facular regions.

Here we report similar measurements, but extended to much greater heights, using the larger diameter 40 cm coronagraph and an excellent 16-bit CCD camera and also, using an eclipse spectrograph to perform more deeper spectra. Depending of the parts of the corona under investigation, our results differ from those of Singh et al. We also consider weak polar coronal regions. It is the first time that a CCD analysis of line profiles is performed so far in the corona using the Fe XIV line.

Furthermore, it is important to mention that line profile analyses of resonance lines like the HI Ly α line and the OVI doublet near 103 nm, performed with the UVCS instrument of SoHO, already provided strong evidence of very large effective ion temperatures above coronal holes (see, e.g. Cramer, 2002). Additional effects could also be considered in terms of very large non-thermal velocities. However, the use of a line coming from a “heavy” ion like the Fe XIV ($m=56$) which is produced at a truly coronal temperature ($\log T_m = 6.3$) presents some interesting advantages, compared to lines used with UVCS were $m=16$ and $\log T_m = 5.5$ for OVI. Finally, in addition to results from SUMER mentioned above, we should notice some new CDS (SoHO) results by O’Shea et al. 2005 using the MgX lines ($\log T_m = 6.0$), which appeared recently and that could be partly compared to ours.

3. CORONAGRAPHIC RESULTS

We performed a set of observations extended over several weeks, but only the best data collected on March 31, 2002 are discussed here. The details of these observations performed at the focus of the NSG of the NSO/SPO 16' Lyot coronagraph have already be described by Contesse, Koutchmy and
have a reduced atmospheric aureola background as measured with the Evans's sky photometer of Sacramento Peak Observatory, but still before the hours of important heating due to solar irradiation which generates large seeing effects in both the Earth's atmosphere and inside the coronagraph. Spectra were obtained between 15:30 and 18:00 UT on March 31, 2002. The 100 μm width slit, corresponding to 2" on the sky, was put orthogonally to the local radial direction, at selected radial distances, \( r \), and consecutively at different positions exactly above the N, E, S, and W limbs (see Fig. 3). We used a dispersion similar to what was used by Tsubabi (1975); other parameters, such as the set-up after the exit of the spectrograph, were similar to what has been used by Koutchmy et al. (1983) at the same instrument to get photographic time sequences to search for Fe XIV oscillations. The resulting spectral dispersion was 4.05 pm per pixel, taking into account the 9 μm pixel size of the Kodak KAF 1602E chip. After the re-imaging Micro-Nikkor lens and a field lens an almost perfect flat field over the whole chip was obtained (no trace of vignetting effect could be detected over the whole field). The adjusted effective exposure time was 5 s, just enough to avoid any saturation of the chip and provide the best signal/noise ratio over a 16-bit dynamic range. The cosmetic property of the cooled chip at −20 C was found excellent, judging from different calibration spectra, including solar spectra taken with the diffuser put in the light path of the coronagraph. We accurately removed the bias and dark currents from each frame and for each selected position shown on Fig. 3. We consecutively recorded five frames in order to improve, after averaging the set, the signal-to-noise ratio over profiles which were extracted from the resulting images. Before averaging, individual spectra were co-aligned with a precision of 1/10 of a pixel in the spectral direction (note that the observed shifts of the overall spectra never exceeded one pixel for each set) and geometric distortion effects were removed. Regarding the other direction, note that the instrument uses a 4-quadrant-cell system of guiding to keep the same region on the slit during the recordings of each set of spectra, although the seeing is the real factor limiting the spatial resolution. An additional smearing is produced by the temporal averaging (typically 2 to 5 min averages).

A very important step in analysing the spectra is the removal of the background aureola parasitic light scattered inside the instrument, \( A_i(r) \), superposed on the light coming from the sky, \( A_s(r) \), which is mainly produced by the forward scattering by aerosols. The summed intensity corresponds to the intensity of the so-called aureola, which decreases drastically when going away from the limb. All components of the aureola are coming from the solar disk illumination and evidently contain all the Fraunhofer lines of the solar spectrum. We tried several methods for removing the background, including some convoluted spectra computed from the AFGL solar irradiance atlas of Sacramento Peak Observatory, using a spectral smearing function of slightly different widths. Finally, the best background cancellation was obtained using spectra taken before and after the series, over the aureola at a large radial distance in polar directions and normalizing each reference spectrum with the effectively measured intensity of the "continuum" near the coronal line. See CKV 2004 for more details concerning the whole procedure of processing the data set, including corrections made on spectra for the rather small instrumental smearing.

The fitting of line profiles and the computation of their FWHM has been well described by Tsubaki (1975) and recently by Kim (2000) and again in the Singh et al. (1999, 2002, 2003) papers, such that we do not consider it useful to repeat or duplicate here this part. The same is true for the extraction of the Doppler temperature, \( T_D \), and of the turbulent velocities, \( V_t \), making the assumption that the full profile is due to the superposition of thermal velocities at the formation temperature of Fe XIV, \( T_m \), and to unresolved turbulent and isotropic velocities \( V_t \), (also called non-thermal velocities), smearing the profiles integrated along each line of sight. Assuming that \( T_m \) is known from the ionisation balance calculations, and taking 55.85 for the atomic mass number of the Fe 13+ ions responsible for producing the Fe XIV line, it is easy to deduce a quite simple and practical formula relating the different parameters:

\[
V_t = 17.2 \text{ km/s} \left( T_D/\text{MK} - T_m/\text{MK} \right)^{1/2}
\]

We take \( T_m = 1.8 \text{ MK} \), i.e. to be equal to the temperature of maximum ionic fraction from

![Figure 4 - Radial variations of the turbulent velocities for different locations in the corona. Error bars correspond to the true dispersion of velocities measured at each position of the slit at a constant radial distance. Note the definite increase of velocities observed above the North Polar Region.](image-url)
Arnaud and Rothenflug, 1985. The measurements show that in the inner corona $T_D$ never reaches a value under 1.8 MK, which corresponds to a FWHM of 0.068 nm (see Kim, 2000).

Fig. 4 indicates the radial variations of the obtained average values of the turbulent velocities as deduced using formula (1), in all directions N, E, S, and W. The indicated uncertainties give the whole range of velocities we got for each position of the slit, which means the true dispersion given by the coronal conditions and not intrinsic uncertainties in measurements which are significantly lower. Furthermore, we performed a correlation analysis between the FWHM observed at different well characterized (relative maxima and relative minima) positions along the slit with different radial distances and the corresponding relative Doppler shift (with respect to the wavelength of the average intensity for each radial position). We also computed the dispersion observed over each time series (5 spectra obtained at each radial position). The results are shown on Fig. 5.

Finally, a power spectrum analysis was performed using a new time series of 256 spectra obtained at the constant position near the E-limb situated at 3 arcmin from the limb. The cadence was 9 sec. An impressive movie was assembled to show the line shifts with high temporal resolution. The analysis was made at several positions along the slit and the average power spectrum is shown on Fig. 6.

4. Eclipse results

We show here only a small part of eclipse results. The experiment was successfully run in 1994, 1999 and in 2001.

The instrument used to carry out this type of experiment is the spectrograph of the coronograph which is put on a rigid mount.

The exposure time had been fixed to 4 s. The photographic film Technical Pan was pushed to 20000 ASA during the development (15 min at 24°C). Let us note that ultra-sensitive film TP 3200 and a motorized camera was preferred to a CCD primarily for two reasons: (i) Advantage of speed at high cadence (less than one second lost between two frames); (ii) Security and ease of use. On the other hand the film must be calibrated carefully because of the non-linearity of its response. This calibration was carried out using the spatialized sensimeter of the Salouf-7 experiment PCN (see...
Koutchmy and Verlhac, 1985); we got results very close to the specifications given by Kodak-Rochester. Further, the spectrum of the green line was analysed in terms of profiles using a microdensitometer, profiles from which we measured the widths at half maximum (FWHM), after having obviously calibrated very precisely the response of the film, and after subtraction of the continuum coronal background. An other series of measurements was done again recently after re-scanning the spectra. On Fig. 8 we show the corrected for instrumental smearing FWHM at different typical radial distances as a function of the corresponding relative central intensities. An interesting feature that we noticed on these spectra is the narrowing of the line when looking at the larger radial distances, say beyond 1.5 R\(_s\). This is finally illustrated on Fig. 9 which shows the most representative results coming from both the coronographic observations and the 2001 eclipse observations.

5. CONCLUSIONS

For a summary, we refer the reader to the abstract given at the beginning of the paper. Briefly, we emphasize the most solid results:
- The line profile analysis of the Fe XIV 530.3 nm line provides an excellent diagnostic of the dynamical state of the corona; the availability of a large flux of photons makes possible observations with a good cadence, near 1s;
- The macro-turbulence is now partly resolved in flows (Lo.s. effects), including enhanced flows in C.H. and bulk (net) flows in equatorial regions at r > 1.5 R\(_s\), where narrower profiles are recorded;
- Oscillations and waves are seen thanks to their Doppler signature and need a more careful analysis using wavelet methods.

Clearly, much more data are needed, including long time series, to see for ex. effects produced by “passing” CME’s. We hope that future experiments planned in space, to perform artificial eclipses using “associated” satellites in rather high orbits (the ASPICS mission) will permit to use this excellent diagnostic made with the “green” line, together with high S/N imaging of the W-L corona.

Finally we note that the results discussed here were the priority of the projected experiment C1 of Lasco performed only partially on SoHO due to the failure of the scanning Fabry-Perot after the freezing of the spacecraft.

9. REFERENCES

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